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MODIFICATION OF RZWQM FOR SIMULATING SUBSURFACE DRAINAGE BY ADDING A TILE FLOW COMPONENT

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ABSTRACT. *Fluctuating water table and subsurface drain flow components were incorporated in the Root Zone Water Quality Model (RZWQM) to enable the model to simulate subsurface drain flows. Parameters in a modified model were calibrated using observed subsurface drain flows for 1990. Model performance was evaluated by predicting subsurface drain flows for 1991 and 1992 by using the calibrated parameters and comparing the predicted drain flows with observed subsurface drain flows for the same years. The modified RZWQM model, in general, showed a good response to rainfall in terms of time of peak flows. However, the modified RZWQM model overpredicted total tile flows by an average of 13%, and the magnitudes of peak tile flows were generally underpredicted. Selected soil properties (bulk density, macroporosity, and residue content) in the surface horizon were changed to investigate tillage effects on tile flows using the modified RZWQM. Four different tillage systems, chisel plow (CP), moldboard plow (MB), no-tillage (NT), and ridge-tillage (RT), were considered. Predicted tillage effects on subsurface drain flows were consistent with the observed effects (i.e., maximum tile flow for NT and minimum tile flow for MB).* **Keywords.** *Subsurface drainage, Water quality, Hydrologic modeling.*

Agricultural drainage is defined as the removal and disposal of excess water from agricultural land by means of surface and/or subsurface drainage methods (USDA-SCS, 1973). Artificial drainage systems are needed to supplement natural drainage and enhance crop growth conditions. Artificial drainage has made agricultural development possible on much of the most productive land in the United States. Subsurface drainage of wet areas alters the time and route by which excess precipitation reaches surface waters. Decreases in the amount of overland flow, increases in percolation, lowering of the water table, and alteration in the flow path of some of the infiltrated water result from subsurface drainage (Baker and Johnson, 1976).

On the other hand, tillage practices directly affect the soil water properties of surface soil and therefore the leaching characteristics (Kanwar et al., 1988). Tillage also disturbs the macropores, whereas no-tillage allows macropore systems to develop and persist. Macropores can act as preferential pathways for rapid movement of water and chemicals to the groundwater. Because of concerns about nonpoint source pollution, the fate of agricultural chemicals under different tillage systems is of considerable interest and importance. Therefore it is necessary to understand all the factors that affect chemical transport and fate. Investigating the quantity and quality of subsurface drainage water under different tillage systems can be helpful in understanding the leaching characteristics of soil under different tillage systems and in determining the suitable tillage practices for water quality enhancement. For example, Kanwar and Baker (1991) studied the effects of four tillage systems namely, chisel plow (CP), moldboard plow (MB), no-till (NT), and ridge-till (RT) on the quantity and quality of subsurface drain flows. They reported that greater drain flows from no-tillage plots under continuous corn resulted in larger NO_3-N losses in comparison with NO_3-N losses from other tillage systems. Several other studies have been conducted to measure the loss of NO_3-N through subsurface drainage (Burwell et al., 1976; Taylor and Thomas, 1977; Gast et al., 1978; Baker and Johnson, 1981; Gold and Loudon, 1982; Kanwar et al., 1985, 1988, 1993a, b; Randall and Nelson, 1985).

Besides experimental investigations, a number of modeling studies have been conducted involving the development and utilization of mathematical models to simulate subsurface drainage. Kirkham (1958) developed an analytical solution for steady state flow to parallel tile drains in a homogenous soil underlain by impermeable layers. Dutt et al. (1972) and Duffy et al. (1975) developed mathematical models of biophysiochemical processes that could be applied to a tile-drained agricultural area. Skaggs (1978) developed a computer simulation model DRAINMOD that simulates the movement of soil water as affected by various subsurface water-management systems. DRAINMOD has been extended further as DRAINMOD-N for predicting nitrogen (N) transport, uptake, and transformation in artificially drained soils. Kanwar et al. (1983) developed a computer simulation model to simulate N losses with tile drainage water. Scotter et al. (1990) developed a simple numerical solution for transient soil water flow to a mole drain for assumed or measured values for rainfall, evaporation, deep percolation, drain spacing, and depth. Workman and Skaggs (1990) developed a water-management model capable of simulating preferential flow. However, none of these models

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incorporates the tillage effects on subsurface drainage flows and drainage water quality.

The main purpose of this research was to develop a comprehensive subsurface drainage flow model by incorporating a fluctuating water table and tile drainage component into the Root Zone Water Quality Model, RZWQM (USDA-ARS, 1992a). The RZWQM model is a process-based, integrated model for simulating the soil-water-plant-atmosphere system. This model can be used for analyzing the effects of various agricultural management practices, including tillage, both on the subsurface environment and crop production. Adding a tile drainage component makes this model capable of simulating subsurface drain flows and evaluating the impact of different agricultural management systems on subsurface drain flows. The specific objectives of this research were to:

- Develop a fluctuating water table and subsurface drain flow component and incorporate it into the RZWQM.
- Calibrate and evaluate the performance of the modified RZWQM model by simulating subsurface drain flows for multiple years. Demonstrate tillage effects on simulated tile flows by changing the input soil properties for the surface horizon.

Development of a Tile-drainage Component

To enable RZWQM to accurately simulate the hydrologic processes in soils having subsurface drainage, a subsurface drain flow component was added to RZWQM (ver. 1.0). For this purpose a new soil water redistribution submodel (MOIST) was developed. This new submodel was capable of simulating fluctuating water table and subsurface drain flows as a function of water table depth. Submodel MOIST was incorporated in RZWQM to replace the original soil water redistribution submodel. The following sections describe the soil water redistribution (MOIST) and subsurface drain flow (TDRAIN) subroutines in detail.

Water Movement Submodel (MOIST)

The soil water redistribution component calculates the unsaturated and saturated flow rates of water within the soil profile after infiltration. It also calculates the daily water table depths and drainage into tiles. This component is based mainly on the soil water redistribution procedure described by Kanwar et al. (1983), and also used by Saxton et al. (1977) and Carcel et al. (1984).

The water content in the soil (θ) is expressed on a volume basis. In the model, the soil water for a given layer varies between wilting point and field saturated water content (specified as 90% of the saturated water content). Wilting point is defined as the water content at 1500 kPa ($\theta_{1500\ kPa}$), below which it is assumed that no evapotranspiration (ET) and no flow occurs through the soil. Field saturated water content is defined as the maximum amount of water held by the soil (θ_s). Above the water table, water content is assumed to vary from $\theta_{1500\ kPa}$ to water content at field capacity ($\theta_{33\ kPa}$). This procedure is not only simple but also eliminates extensive computing time and mass balance errors (instability of solution) involved with the numerical solution of Richards equation. Because the properties of the actual soil profile are heterogenous the values of wilting point and field capacity are functions of depth in the model. A variable-depth scheme (layer thickness ranging from 10 mm at the top to 250 mm at the bottom) is used to divide the 2.72-m-deep soil profile into 26 layers. The procedure for dividing the soil profile in different layers is discussed in detail in RZWQM technical documentation (USDA-ARS, 1992a).

The MOIST subroutine is called in each time step (1 h). A water content profile, potential ET rate, soil physical and hydraulic properties, and depth to water table are input to the subroutine. Subroutine MOIST first checks the water table depth and divides the profile into saturated and unsaturated zones. Next, it calculates ET values from unsaturated layers and determines average inter-layer hydraulic conductivity (K) and soil water diffusivity (D). The value of potential evapotranspiration (PET) is passed from the main model to the MOIST subroutine. This value of PET is divided by the number of layers in the unsaturated zone to calculate ET from each layer. If a given soil layer can meet the demand of required ET (i.e., after reducing total volume of water in this layer by ET the final $\theta > \theta_{1500\ kPa}$), then the total volume of water in this layer is reduced by ET, otherwise ET from this layer is calculated as $(\theta - \theta_{1500\ kPa}) *$ layer thickness. When the water content of a given layer is greater than $\theta_{33\ kPa}$, excess moisture ($\theta - \theta_{33\ kPa}$) is drained to the next layer. If the water content for a given layer is below $\theta_{1500\ kPa}$, drainage and ET from this layer are stopped. If the water content is between $\theta_{33\ kPa}$ and $\theta_{1500\ kPa}$, flow rate to the next layer, is calculated by the following equation (Beek and Frissel, 1973):

$$V_i = -D_i(\theta)\left[\frac{d\theta}{dx}\right] + K_i(\theta) \quad (1)$$

where

V_i = flow rate of water (mm/h) in layer i
D_i = average soil water diffusivity (mm^2/h) in layer i
θ_i = water content of soil (mm^3/mm^3) in layer i
x = thickness of soil layer i (mm)
K_i = hydraulic conductivity of soil (mm/h) in layer i

This differential equation can be written as a set of finite difference equations when water flows down from one layer into another layer. The flow rate between layers is calculated according to the following equation:

$$V_i = -D_{i-1/2}\left[\frac{\theta_{i-1} - \theta_i}{X}\right] + K_{i-1/2} \quad i = 1 \ldots L \quad (2)$$

where

X = average thickness of layers i and i–1 (mm)
$D_{i-1/2}$ = $[D(\theta_{i-1}) + D(\theta_i)]/2$ average diffusivity (mm^2/h)
$K_{i-1/2}$ = $[K(\theta_{i-1}) + K(\theta_i)]/2$ average conductivity (mm/h)
L = index of the layer just above the layer containing water table

Hydraulic conductivity $K(\theta)$ is determined in RZWQM by the functional form suggested by Brooks and Corey (1964) and is passed to MOIST from the main model.

Diffusivity $D(\theta)$ is calculated by using a function adopted from Staple (1969) for loam soil.

Finally, the thickness of the unsaturated zone and the water table depth are updated after redistribution of moisture and tile drainage is calculated as a function of the updated water table depth.

Changes were also made in the macropore flow component of the model. In RZWQM the excess water left in the macropores after lateral infiltration to the soil matrix was directly drained out of the soil profile to satisfy free-flow boundary condition at the bottom. This component was modified to add this excess water from the macropores directly to the subsurface drain flows. Adding macropore flow directly to tile flow is reasonable based on evidence from Everts and Kanwar (1990) that preferential flow contributions to drain flow start immediately after irrigation starts and ends soon after irrigation was stopped.

Subsurface Drain Flow Component (TDRAIN)

This component (submodel TDRAIN) is based on the tile flow component of DRAINMOD (Skaggs, 1978). The submodel TDRAIN first calculates the thickness of the saturated zone and the effective lateral conductivity. Lateral saturated hydraulic conductivities vary with depth and are input to this component. Drainage flux is calculated by the steady-state Hooghoudt equation:

$$\mathrm{DFLUX} = 4.0\,K\,E_m\left[\frac{2.0\,H_d + E_m}{S^2}\right] \tag{3}$$

where

S = drain spacing (mm)

H_d = equivalent depth of the impermeable layer from the center of the drain (mm)

DFLUX = drainage flux (mm/h)

K = effective lateral hydraulic conductivity (mm/h)

E_m = elevation of water table above the tile drains (mm)

The basic assumption of this equation is that the lateral water movement occurs mainly in saturated regions. Although drainage is not a steady-state process, the above equation has been used successfully by Skaggs (1978) and Kanwar et al. (1983) considering that for a short enough time step (1 h in our model) water table depth can be assumed as constant. Effective lateral hydraulic conductivity in equation 3 is calculated by the procedure described by Skaggs (1978). The values of lateral hydraulic conductivities and other parameters related to drainage flux are given in the next section.

After calculating total tile drainage by the Hooghoudt equation, tile drainage per unit thickness (UDRN) is calculated for the saturated zone. The water contribution (DEL) from each layer is then calculated by multiplying UDRN by the thickness of the layer. Water content of each saturated layer is reduced by the amount DEL and the depth of water table is updated based on the new water content profile. After de-saturating soil layers in the saturated zone, water content deficit $(\theta_s - \theta)$ in a given soil layer 'i' is met by routing water from the previous layer 'i-1'. This procedure starts from the bottom layer in the saturated zone. At the end, the top layer in the saturated zone is checked for its water content. If its water content is less than $\theta_{33\ \mathrm{kPa}}$, it is considered in the unsaturated zone and the water table is lowered to the next layer. Otherwise the water table is still considered in this layer. At the end of the day, hourly drainage flux is added together to determine daily subsurface drainage flux.

Field Experiments and Input Data Needs

The modified RZWQM was first calibrated using observed subsurface drain flows for the year 1990, and then its performance was evaluated by comparing simulated subsurface drain flows with the observed flows for years 1991 and 1992. Observed subsurface drain flow data was collected from a water quality site at Iowa State University's Northeast Research Center (NERC) near Nashua, Iowa (Kanwar et al., 1993a). The following sections describe the experimental site, measured tile flow data, and the input data needed for simulations in detail.

Description of the Experimental Site and Observed Tile Flow Data

The study site is located on a predominantly Kenyon loam soil with 3 to 4% organic matter. These soils have seasonal high water tables and benefit from subsurface drainage. Sixty meters of pre-Illinoian till units overlie a carbonate aquifer. However, in some areas bedrock is near the surface. The site has thirty-six 0.4-ha experimental plots with fully documented tillage and cropping records for the past 14 years. Tile lines were installed about 1.2 m deep at 28.5 m spacings in 1979. Each 0.4-ha plot has one tile line passing through the middle of the plot and there is a tile line at each of the plot borders. The middle tile lines of all the plots were intercepted and connected to individual sumps in December 1988 for measuring subsurface drainage and collecting water samples for chemical analysis. A detailed description of the automated subsurface drain monitoring system is given by Kanwar and Baker (1991).

Long-term tillage studies (three replications of each tillage treatment) were initiated at this site in the fall of 1977 to evaluate the effects of CP, MB, NT, and RT systems on subsurface drainage water quantity and quality.

Model Input Data

Climatic Data. The model requires daily input values of air temperature (minimum and maximum), wind speed, short-wave radiation, pan evaporation, and relative humidity. All the daily climate data were available for the Nashua weather station except wind speed and pan evaporation. When the data on wind speed are missing, the model assumes a wind speed of 10 km/day. When the pan evaporation value is not supplied, the model uses short-wave radiation as the energy input into the evaporation algorithm and estimates pan evaporation.

The model requires values of surface albedos for dry and wet soil, mature crop and residue, and sunshine fraction as input. These albedos provide the base values of energy reflectance from these surfaces. The albedos are modified as environmental conditions change. Surface albedos were taken from Jury et al. (1991). The sunshine fraction is estimated based on latitude information provided as input to the model. The model uses the Shuttleworth and Wallace (1985) approach to calculate daily ET.

The model requires input of rainfall data as breakpoint rainfall data. If a given rainfall event is plotted as cumulative rainfall as a function of time, each point where there is a substantial change in slope (representing a change in rainfall intensity) will represent a breakpoint. For the simulations for 1990, 1991, and 1992, hourly rainfall data from the Nashua weather station were acquired. To convert hourly rainfall data into breakpoint rainfall data, cumulative rainfall was plotted as a function of time for each rainfall event and breakpoints were recorded wherever there was a substantial change in the slope of the cumulative rainfall versus time curve. For the period when hourly rainfall data were not available (rain gage damaged or datalogger not working), daily rainfall values were obtained from the NERC nonrecording rain gage observations. A similar rain event (approximately equal in magnitude) was selected from hourly rainfall data for the Nashua weather station. The pattern of this hourly rainfall was used to estimate breakpoints for the missing rainfall event.

Soil Properties Data. A 2.72-m-deep soil profile was considered for simulation. This profile was divided into eight soil horizons. First seven soil horizons (covering a soil profile up to 1.67 m) were delineated based on the information gathered from soil survey reports for Kenyon loam (USDA-SCS, 1982). Eighth horizon covered the soil profile from 1.67 to 2.72 m. Soil properties for this horizon were assumed to be the same as for seventh horizon. For each horizon, physical soil properties, e.g., soil bulk density (BD), porosity (estimated by BD and a particle density of 2.65 kg/m^3), macroporosity (MP), and particle size distribution were used as input to the model. Soil bulk density for the surface horizon, and particle size distribution at various depths of the profile were experimentally measured. Singh (1994) described the detailed methods of these measurements. For subsequent horizons, soil BD data were adopted from Sharpley and William (1990). Among soil hydraulic properties, only $\theta_{33\ kPa}$ for each soil horizon was taken from Sharpley and William (1990) and specified as input. All other hydraulic properties, such as saturated hydraulic conductivity, effective porosity, and bubbling pressure, were estimated by the model based on BD, $\theta_{33\ kPa}$, and texture data. Table 1 shows some major soil properties for each soil horizon.

Input data on soil heat properties consisted of dry volumetric heat capacity, heat conductivity, and shape factors. Soil heat properties were estimated from soil texture data for each horizon as described by Jury et al. (1991). These are required by RZWQM for evaporation and plant growth submodels. Hydraulic properties are not corrected for temperature.

Plant Growth Variables and Parameters. The RZWQM model uses a generic plant growth model to simulate corn growth. Default values of plant growth parameters were used for the generic growth model, as recommended in the RZWQM user manual. Planting and harvesting days, number of plantings, planting depth, planting density, harvesting efficiency, etc., are input to the model and were based on the actual field information collected at the research site.

Tillage Management Variables. The RZWQM model needs tillage-related information to simulate tillage effects on soil properties (bulk density, macroporosity, and residue incorporation). This information mainly consists of date of tillage, tillage implement used, depth of tillage, tillage intensity, etc. However, tillage effects for this simulation study were incorporated by using field-measured values of BD, residue cover, and incorporated residue amount for the surface horizon as a function of tillage. Macroporosity was subjected to calibration for each tillage system. Field-measured values were considered to more accurately represent actual field conditions rather than depending on empirical functions used in RZWQM to estimate these parameters as a function of tillage.

Model Simulations and Evaluations

Boundary and Initial Conditions

To simulate fluctuating water table conditions, an impermeable layer was assumed at a depth of 2.72 m, which is quite a reasonable assumption for this site. Deep seepage through this impermeable layer was set equal to zero. The upper boundary of the soil profile system being

Table 1. Soil properties for different soil horizons used as input for subsurface drainage simulations

Horizon Number	Depth (m)	θ_{33kPa}* (m^3/m^3)	Bulk Density* (kg/m^3)	Porosity (m^3/m^3)	Organic Carbon† (%)	Particle Size Dist. (%)†		
						Sand	Silt	Clay
1	0.00-0.20	0.30	*‡	*‡	2.0	38	42	20
2	0.20-0.41	0.27	1.52	0.43	0.8	41	34	25
3	0.41-0.50	0.26	1.55	0.42	0.6	42	32	26
4	0.50-0.69	0.28	1.60	0.40	0.4	43	30	27
5	0.69-0.89	0.28	1.65	0.38	0.3	44	28	28
6	0.89-1.23	0.26	1.70	0.36	0.2	44	31	25
7	1.23-1.67	0.28	1.75	0.34	0.2	44	31	25
8	1.67-2.72	0.28	1.75	0.34	0.1	44	31	25

* Taken from Sharpley and William (1990).
† Experimentally measured (Singh, 1994).
‡ Experimentally measured as a function of tillage (see table 3).

modeled was characterized by infiltration and evaporation rate at the surface layer.

Initial soil water content profile, temperature profile, water table depth, organic matter content, and chemical concentration profiles were needed as input to the model. Initial soil water content was subjected to calibration. In the first simulation run, it was set equal to $\theta_{33\ kPa}$ (field capacity), but adjusted in the subsequent simulations to begin the tile flows approximately at the same time tile flows actually began in the field. Table 2 shows adjusted initial water contents for the profile for 1990. Initial water table depth was set equal to 1.2 m (equal to depth of tile drains). Organic carbon contents were determined for Kenyon loam as a function of depth (Singh, 1994) and were used as initial values in the model. Organic carbon values ranged from 2% at surface to 0.1% at 1.5 m depth at this site. The initial temperature profile was adopted from Hillel (1982) for the spring season. Table 2 shows initial soil moisture and temperature profiles, used for the final simulation runs in this study.

Model Calibration

Subsurface drain flow data from 1990 were used to calibrate the model. Tile flows were simulated for the growing season of 1990 under different tillage systems (CP, NT, MB, and RT) and compared with the observed tile flows recorded at the NERC water quality research site at Nashua. Tillage systems were characterized by BD, macroporosity (field-measured, Singh, 1994), surface residue cover (estimated from crop yield and percent cover data; Wischmeier and Smith, 1978), and incorporated residue amount for the surface horizon. Incorporated residue amount (Mg/ha) was calculated as the difference between residue amounts before and after tillage, based on the residue amount estimation technique of Wischmeier and Smith (1978), assuming no residue losses during the tillage operation. Incorporated residue amounts were further converted into slow (structural) and fast (metabolic) pools based on a C:N ratio (40 for corn) as described in RZWQM user's manual (USDA-ARS, 1992b). Table 3 shows input values of these variables for each tillage system. Measured tile flow data were collected from the Nashua water-quality site. Tile flows were continuously monitored for 1990, 1991, and 1992 to investigate tillage effects on subsurface drain flow quantity and quality (Kanwar and Baker, 1991). Cumulative tile flows were recorded three times a week, and a linear interpolation was used to calculate daily tile flows.

Table 2. Initial soil water content and temperature profiles for simulations for 1990

Horizon	Water Content (m^3/m^3)				Temperature
Number	CP*	MB†	NT‡	RT§	(° C)
1	0.20	0.20	0.20	0.20	23
2	0.22	0.22	0.22	0.22	21
3	0.23	0.23	0.23	0.23	19
4	0.23	0.23	0.24	0.23	18
5	0.23	0.23	0.24	0.23	18
6	0.24	0.24	0.26	0.24	19
7	0.31	0.31	0.31	0.31	20
8	0.31	0.31	0.31	0.31	20

* Chisel plow.
† Moldboard plow.
‡ No-tillage.
§ Ridge tillage.

Table 3. A list of input soil properties for the surface horizon (0 to 200 mm) and their values for different tillage systems

Soil Property	CP*	MB†	NT‡	RT§
Bulk density (kg/m^3)	1.41	1.38	1.50	1.38
Porosity (m^3/m^3)	0.47	0.48	0.43	0.48
Macroporosity (m^3/m^3)	0.0	0.0	0.004	0.0
Residue pools (μg/g)				
Slow pool	450	700	140	310
Fast pool	700	1000	215	480
Surface crust	No	Present	No	No
Residue cover (Mg/ha)	3.8	0.6	6.2	5.0

* Chisel plow.
† Moldboard plow.
‡ No-tillage.
§ Ridge tillage.

A surface crust (conductivity = 2 mm/h) was specified in the case of the MB treatment, and all macropores were assumed to be disrupted by tillage (macroporosity was set equal to zero). Freese et al. (1993) reported, based on their experiments, that surface sealing was more important than bulk density or porosity in reducing infiltration rates in MB plots. Macropores are not effective when a surface crust is present, which is the case in MB plots. Roth et al. (1988) also confirmed that porosity has little influence on infiltration when a surface seal is present. For the rest of the tillage treatments, field-measured macroporosity was used first, but was calibrated in subsequent trial runs to minimize the error between total observed and predicted tile flows for 1990. Calibrated macroporosity values for 1990 are given in table 3 for each tillage system.

The criterion used for calibrating the model was to minimize the difference between the measured and predicted cumulative tile flow for the growing season of 1990 [day of year (DOY) 100 to 300; 10 April to 27 October]. A trial and error procedure was used to determine the best value of any parameter that could not be physically measured and some that were measured, such as macroporosity. Each parameter was varied within a reasonable range while all other parameters were kept constant. The procedure was continued until an acceptable value for the parameter was obtained. A list of various calibrated parameters is given in table 4 along with their input values.

Figures 1, 2, 3, and 4 show measured and predicted tile flows under CP, MB, NT, and RT tillage systems, respectively, for the growing season of 1990. There is generally good agreement between measured and predicted values, although discrepancies exist for some days. The coefficient of determination (R^2) was calculated for the observed versus predicted flows under each tillage treatment. The R^2 values for these simulations ranged from 0.49 (for MB) to 0.62 (for NT). The model predicted peak tile flows at approximately the same time they were actually observed and also predicted zero flow within a few days after the tiles actually stopped flowing. Some of the discrepancy between the predicted timing and observed

Table 4. Summary of input parameters for tile-drain subroutine

Parameter	Calibrated or Known Value
Drain spacing	28.50 m
Drain depth	1.20 m
Actual depth from drain to imp. layer*	1.52 m
Equivalent depth from drain to imp. layer*, H_d	1.30 m
Lateral hydraulic conductivity*	
Horizon 1	15.5 mm/h
Horizon 2	10.5 mm/h
Horizon 3	11.8 mm/h
Horizon 4	10.0 mm/h
Horizon 5	10.0 mm/h
Horizon 6	9.5 mm/h
Horizon 7	9.0 mm/h
Horizon 8	9.0 mm/h

* Calibrated values.

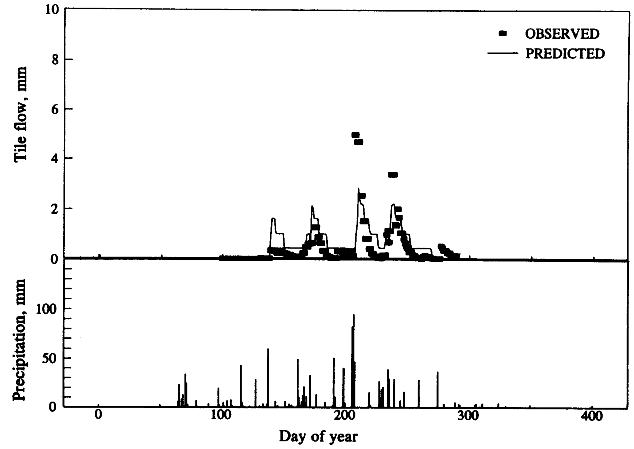

Figure 2–Simulated and observed daily tile flows for moldboard plow (1990).

timing of peak flows could be due the error involved with the linear interpolation of observed cumulative tile flow data. Given the fact that a certain degree of spatial variability exists under actual field conditions, the model predictions were encouraging. Table 5 shows the total predicted and measured flows for 1990.

Even though the model somewhat overpredicted total flows for all the tillage systems, it did predict maximum tile flow for no-till and minimum for MB system, consistent with the observed tile flow data. Although peak flows were usually underpredicted, the model did predict relatively higher peak flows under NT treatment (a macroporosity of 0.004 m^3/m^3 for the surface horizon was specified for the NT treatments) in comparison with the rest of the tillage systems. Thus invoking macropore flow in the model increased tile drainage.

In the case of the NT treatment, tile flow peaks were underpredicted except on DOY 209. It was noted that runoff was generated by the model on DOY 208 and 209, part of which was contributed to tile flow as macropore flow. On other days (where predicted peaks were much lower than observed peaks) runoff was not generated at all by the model. Therefore, there was no macropore flow contribution to simulated tile flows for these days. Thus, even when macropores were present under the NT system, no macropore flow was generated by the model because rainfall intensity was not enough to generate any rainfall excess. Rainfall intensity, therefore, can be critical in predicting accurate tile flows. It seems that macropore flow was actually an important contribution to observed flow for all the storm events where peak flow occurred in NT plots. Observed flow peaks under the other tillage treatments were usually not as high as under the NT treatment for the same rainfall events, indicating less or no soil macroporosity under the other tillage systems compared to the NT system. Other factors that could also contribute to the difference in flow amounts for different tillage systems, but that were not taken into account, were deep seepage and the lateral groundwater flow component.

Consideration should also be given to the dynamic nature of the soil and spatial variability in soil properties. Although the modified model is capable of showing a good response to rainfall pattern, it does not take into account the spatial variability in soil properties. Although the model is capable of predicting temporal changes in the soil properties if tillage is input as a management practice,

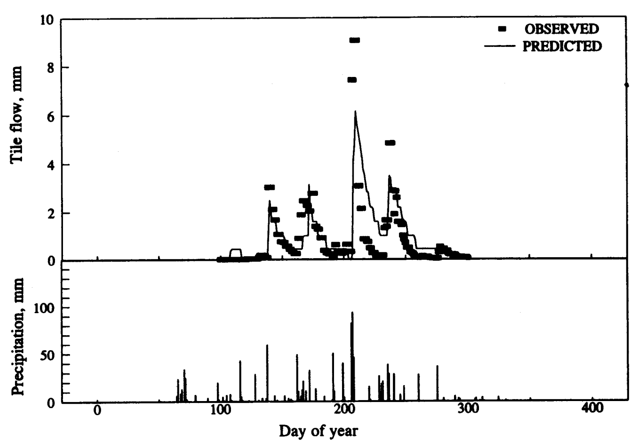

Figure 1–Simulated and observed daily tile flows for chisel plow (1990).

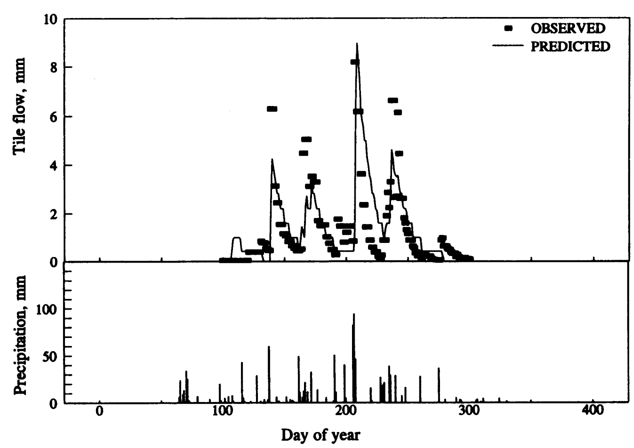

Figure 3–Simulated and observed daily tile flows for no-till (1990).

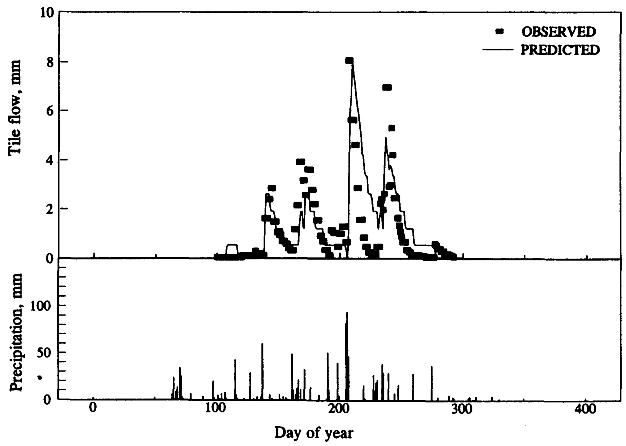

Figure 4–Simulated and observed daily tile flows for ridge-till (1990).

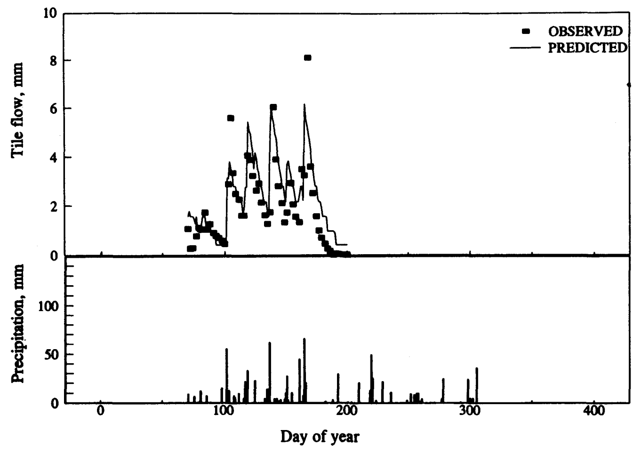

Figure 5–Simulated and observed daily tile flows for chisel plow (1991).

weather-induced changes in some of the soil properties, such as macroporosity, were not incorporated during the simulation period. Using field measured data on BD, MP, and residue amount to characterize tillage treatments did not allow temporal changes in the soil profile. These temporal changes could sometimes be significant. For example, macroporosity of soil is not only a function of tillage, but also changes with crop type, weather patterns, worm activity (related to weather pattern ultimately), soil moisture status, cultivation, etc. No incorporation of spatial variability and temporal changes in the soil properties in these simulations also contributes to the discrepancies in observed and predicted tile flows.

Model Testing and Evaluations

To test the ability of the model to predict system response, the model was tested with tile flow data for 1991 and 1992. Initial water content in the soil profile was adjusted for these simulations to make sure that simulated tile flow began approximately at the same time tile flow actually began in the field. The rest of the input data were the same as for the 1990 simulations. Initial water content, macroporosity, and residue cover amount are given in tables 2 and 3. Simulations were conducted from DOY 70 to 200 for 1991 and from DOY 70 to DOY 250 for 1992. These dates represent the beginning and ending of the observed tile flows. The daily observed and predicted tile flows for 1991 and 1992 are shown in figures 5 through 8 and 9 through 12, respectively.

Predicted tile flows for 1991 compare reasonably well to observed tile flows, except for the RT treatment under which predicted peaks were significantly lower than observed peaks. Total predicted tile flows for the season were also in close agreement with the observed flows (table 5), except that under the CP treatment the model overpredicted total tile flow by about 14%. Coefficient of determination (R^2) was calculated for the best-fit lines for observed versus predicted daily tile flow data. The R^2 values for 1991 tile flow simulations ranged from 0.69 (for CP treatment) to 0.54 (for RT treatment). Again, the

Table 5. Total seasonal predicted and observed tile flows for 1990, 1991, and 1992

Year	Total Rain	Subsurface Drain Flows (mm)			
	(mm)	CP	MB	NT	RT
1990	939				
(DOY 100-300)	Observed*	183	90	275	191
		(52.6)†	(28.9)	(7.8)	(61.2)
	Predicted	197	107	290	221
	Percent difference	7.6	18.9	5.4	15.7
1991	592				
(DOY 70-200)	Observed*	264	174	312	315
		(46.6)	(28.8)	(26.4)	(41.5)
	Predicted	309	184	315	310
	Percent difference	17.0	5.4	1.0	1.5
1992	732				
(DOY 70-250)	Observed*	80	64	92	70
		(15.4)	(32.0)	(46.2)	(5.4)
	Predicted	88	78	109	96
	Percent difference	10.0	21.8	18.5	37.1

* Average of three replications.
† Standard deviation.

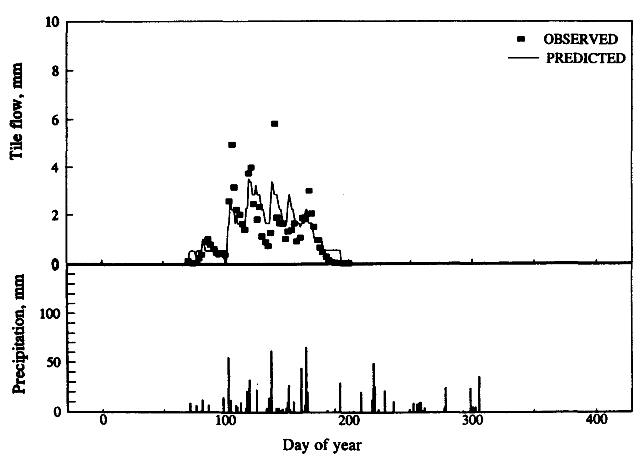

Figure 6–Simulated and observed daily tile flows for moldboard plow (1991).

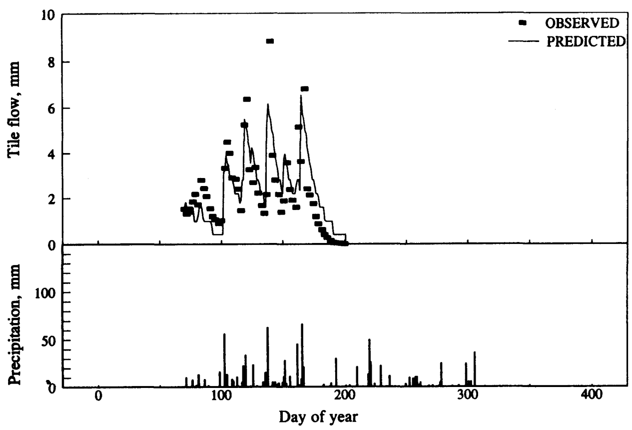

Figure 7–Simulated and observed daily tile flows for no-tillage (1991).

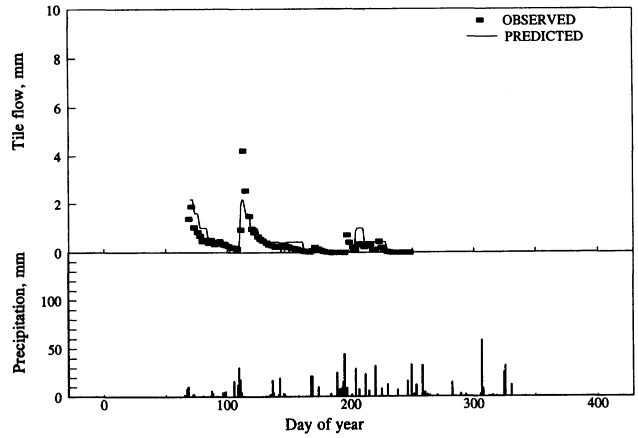

Figure 10–Simulated and observed daily tile flows for moldboard plow (1992).

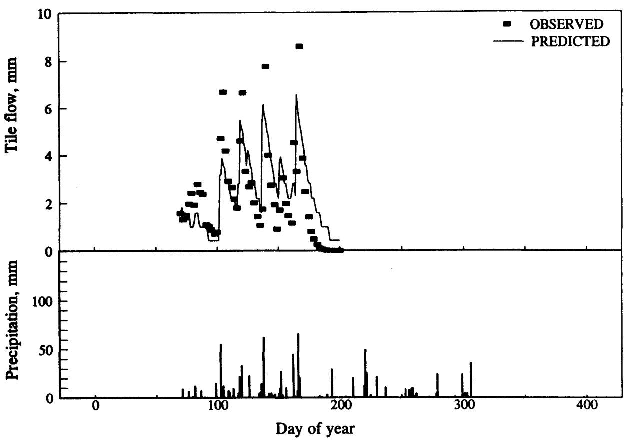

Figure 8–Simulated and observed daily tile flows for ridge-tillage (1991).

reasons summarized in the earlier section may be responsible for these discrepancies. Although total rainfall for 1991 (during the simulation period) was less than the rainfall in 1990, total tile flows were greater, suggesting a higher initial water content in the profile and probably a higher degree of preferential flow, suggesting more macroporosity in year 1991.

Simulated tile flows for 1992 (figs. 9 through 12) again followed the observed trend reasonably well. Although simulated tile flows for 1992 were overpredicted (about 20% on average; table 5), again maximum tile flows occurred under NT and minimum flows occurred under MB treatment, similar to observed trends for this year. The R^2 values for observed versus simulated daily subsurface drain flow data for 1992 ranged from 0.62 (for NT) to 0.69 (for RT). However, tillage effects were not prominent in observed or simulated tile flows for this year in comparison with those in 1990 and 1991. The year 1992 was a relatively dry year, with mostly low-intensity rainfall events. Therefore, in 1992, preferential flow was probably not generated as much as in years 1990 and 1991, thus minimizing the tillage effects on subsurface drain flows.

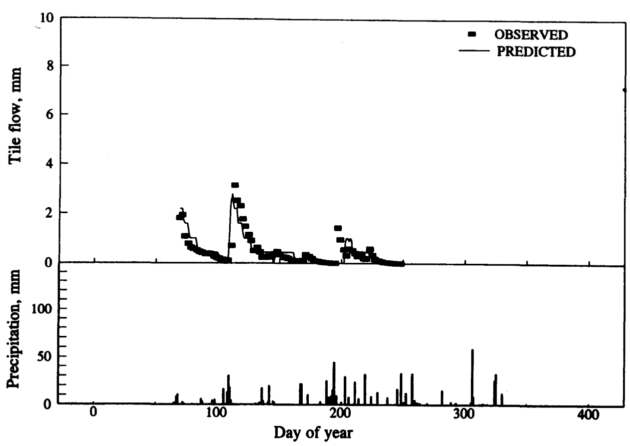

Figure 9–Simulated and observed daily tile flows for chisel plow (1992).

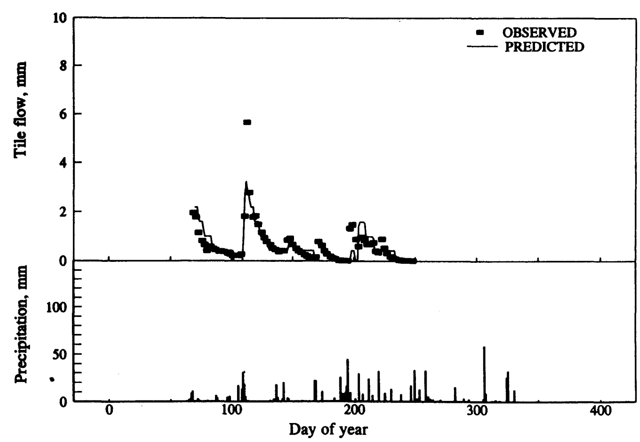

Figure 11–Simulated and observed daily tile flows for no-tillage (1992).

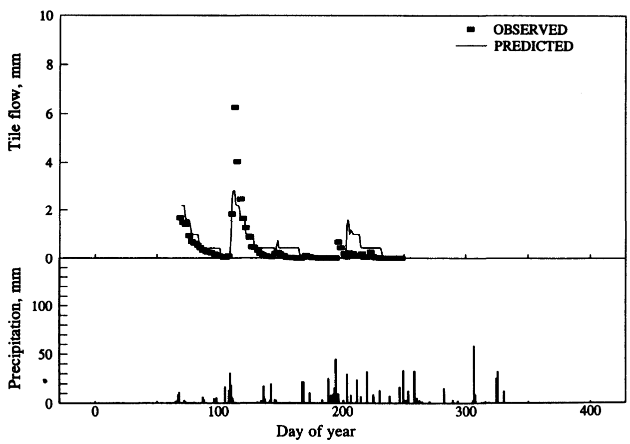

Figure 12–Simulated and observed daily tile flows for ridge tillage (1992).

Summary and Conclusions

- A fluctuating water table and tile flow component was developed and added to RZWQM. Selected soil properties of the top soil horizon (BD, MP, and residue amount) were changed to demonstrate tillage effects on tile flows by using the modified RZWQM.
- The modified model was first calibrated to minimize the differences between the cumulative predicted and observed subsurface drain flows for 1990. The modified RZWQM model showed a good response to rainfall pattern. There was generally a good agreement between the observed and predicted daily subsurface drain flows. Coefficient of determination between observed and predicted subsurface drain flows ranged from 0.49 to 0.62 for 1990 simulations.
- Performance of the modified RZWQM was further evaluated by predicting tile flows for 1991 and 1992 using the calibrated parameters. Although this model overpredicted total tile flows by an average of 13%, predicted tillage effects on tile flows were consistent with the observed effects (i.e., maximum tile flow under NT and minimum under MB). Again, coefficient of determination between the observed and predicted daily subsurface drain flows for 1991 and 1992 ranged from 0.54 to 0.69.

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